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Hybrid steel plate girders subjected to patch loading, Part 1: Numerical study

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ABSTRACT

Extensive research focused on the structural behavior of hybrid steel plate girders is nowadays available in the literature. Furthermore, extensive research devoted to the resistance of homogeneous girders to patch loading has been performed in the last decades. Investigations dealing simultaneously with both fields are, however, rather scarce. The driving force behind developing the present research work has been the aim of completing the knowledge of the patch loading field for the particular structural alternative of hybrid steel plate girder. In the current paper, experimental results found in the literature as well as additional numerical simulations developed by the authors are summarized. The results presented can be used for assessing the resistance of hybrid steel plate girders subjected to patch loading. An in-depth exploit of such results is presented in a companion paper.

1. Introduction

A girder is deemed as being hybrid when it is fabricated with different steel strengths for the flange and web panels. In hybrid design, the nominal yield strength of one or both flanges is larger than the nominal yield strength of the web. This type of girder is popular as the girder yields a greater flexural capacity at lower cost and weight compared to a homogeneous girder [1,2]. Extensive experimental, theoretical and numerical research on hybrid design can be found in the literature. Flexural capacity [3], shear resistance [4,5], instability [6] and fatigue resistance [7] of hybrid prototypes have been widely investigated in the last decades. As a result, hybrid design has proven to be economically sound when used in continuous bridges [8].

On the other hand, the development of modern high strength steels with improved weldability is expected to encourage the designers of bridges to use them in future hybrid girder solutions. Potentially, a certain number of these bridges might be erected by using the incremental launching method. This construction process implies that the reactions of the piers become moving concentrated loads acting in short lengths of the webs assembling the plate girders. A concentrated force acting perpendicular to the flange of a steel girder is commonly referred to as patch loading. This type of loading usually induces a local failure of the web plate in the vicinity of the loaded flange. If the web panel is stocky, the failure mode is primarily dominated by yielding whereas whether the panel is slender, the failure mode is conversely dominated by instability (Fig. 1).

Patch loading phenomena have been widely analyzed since the early sixties. Experimental and theoretical analyses have pinpointed the typical failure mechanisms of girders subjected to patch loading and consequently ultimate load predictions have been provided by researchers [9–12]. Broadly speaking, two approaches have been proposed to describe the resistance of members subjected to this sort of loads. The first approach defines a plastic resistance F_y of the member whereas the second, an elastic critical load F_{cr}. The former has been generally obtained by limit analysis and the latter, by theoretical formulae properly calibrated with numerical simulations. Several failure mechanisms and critical buckling loads have been proposed throughout the last decades for the case of stiffened and unstiffened panels. From these works, it has been demonstrated that the most relevant parameters that influence the response of the girders subjected to patch loading are the following:

- The web thickness t_w.
- The web yield stress f_{yw}.
- The stiff bearing length s_s.
- The flexural stiffness of the flange for bending.
- The existence of transversal and/or longitudinal stiffening.

The factual situations to which these members are subjected lie inside a blurred transition between yielding and instability. It is well known that the square root of the ratio between the plastic resistance F_y and the elastic critical load F_{cr} is commonly referred to as the slenderness parameter $\overline{\lambda}$. Admittedly, there exists a direct relation between $\overline{\lambda}$ and the transition between yielding and instability. This relation has been labeled in the European guidelines EN1993 as the χ–$\overline{\lambda}$ resistance function, in which χ may be defined as the percentage of the maximum plastic resistance F_y that the member is able to achieve when

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Notation

h_w	Clear web depth between flanges
a	Width of web panel (distance between transverse stiffeners)
s_s	Length of stiff bearing
t_f	Thickness of the flanges
t_w	Thickness of the web
t_s	Thickness of the transverse stiffeners
b_1	Distance of the longitudinal stiffener from the loaded flange
f_{yf}	Flange yield strength
f_{yw}	Web yield strength
f_{ys}	Stiffener yield strength
l_y	Effective loaded length
χ_F	Reduction factor due to local buckling
F_y	Plastic resistance
F_{cr}	Critical buckling load
E	Young modulus
ε	Factor depending on f_{yf}
$\overline{\lambda_F}$	Slenderness
γ_{M1}	Partial factor
γ_s	Relative flexural rigidity of the stiffener
w	Maximum scale of the critical shape
M_{pt}	Plastic moment in outer hinges
M_{pf}	Plastic moment in inner hinges
F_{Rd}	Design resistance to transverse forces
$F_{cr,\mathrm{num}}$	Elastic critical buckling load obtained from an Eigenvalue analysis
$F_{u,\mathrm{exp}}$	Ultimate load of girders subjected to transverse forces according to experimental results
$F_{u,\mathrm{num}}$	Ultimate load of girders subjected to transverse forces according to numerical results.

subjected to compressive loads. The patch loading phenomena have been harmonized to this procedure for transversally stiffened girders [13] as well as longitudinally stiffened girders [14,15]. The χ-function is determined by a calibration with existing experimental databases on each case. In recent research works [16,17], additional numerical and experimental tests have enlarged the pool of girders available for proper calibrations.

In this paper, the resistance of hybrid steel plate girders subjected to patch loading is studied. Firstly, it is shown that scant work related to this topic is available. On the other hand, it is demonstrated that the EN1993 predicts the resistance of plate girders subjected to patch loading as a monotonic increasing function with, among other parameters, the flange yield strength f_{yf} (and consequently, with the hybrid grade f_{yf}/f_{yw}). Secondly, a vast numerical study aimed at comparing numerical and theoretical results is presented. In this study, it is found that results obtained with the EN1993-1-5 provisions do not reproduce satisfactorily the trends obtained numerically. Finally, a design proposal aimed at correcting this anomaly is presented in a companion paper. This proposal is in accordance with the χ–$\overline{\lambda}$ procedure implemented in EN19931-5.

2. Review of the earlier work

Despite the vast amount of research devoted to hybrid girders and patch loading, the research work that matches both subjects is rather scant [18,19]. Schillings [18] presented the first and only found publication related to hybrid steel girders dealing explicitly with concentrated loading. The main objective of this work was to assess the influence of the premature web yielding caused by bending in the susceptibility to the phenomena associated with concentrated loading. In order to assess this susceptibility, Schillings performed two tests on the same hybrid specimen. First, a transverse compressive load was applied on the compression flange and second, the transverse load was applied on the tension flange (Fig. 2). The tests showed that concentrated loads can be applied in either tension or compression flanges even when the longitudinal stress in the web is close to its yield strength.

Ultimate load was defined as the load in which linearity of the load–displacement plot was no longer observable. It can, however, be inferred from the experimental observations described by Schillings that those girders were able to undergo higher load capacities than those defined by the authors. The ultimate load P_c was defined by Schillings, according to Eq. (1), as the bearing length, times the web thickness, times the yield strength of the web. Noticeably, the flange yield strength f_{yf} was no taken into account in the calculation if P_c. Ever since, refinements have been implemented in codes and nowadays the predicted ultimate load differs substantially from Eq. (1).

$$P_c = s_s \cdot f_{yw} \cdot t_w. \tag{1}$$

Moreover, when studying the behavior of slender girders subjected to patch loading, Granath [19] pointed out interesting conclusions about the influence of the moment capacity of the flanges on the bearing capacity of plate girders subjected to concentrated loads. The response of slender girders was studied by using numerical simulations for several cases from which some were hybrid. In this work, though not focused in hybrid girders, Granath demonstrated that increasing the yield stress of the web increases considerably the ultimate load capacity of the girders to patch loading while increasing the yield stress of the flange does not. According to Granath [19], there is no yielding of the flange at the low level of deformation occurring at the peak load. It is worth pointing out that this author studied this effect on a limited amount of simulations.

On the other hand, looking attentively the frame of experimental research works (summarized in [13,14,16]), it is observed that around 400 tests on transversally stiffened girders subjected to patch loading are available in the literature. From these tests, it is also observed that a non-negligible amount of girders present a ratio $\Phi_h = f_{yf}/f_{yw} \geq 1.25$ (this value corresponds approximately to upgrading one steel grade in the flange). Presumably, for the vast majority of cases, the girders were not deliberately designed as hybrid. This difference stems in the fact that the measured yield strengths of the web and flanges are rarely identical and consequently, one might obtain greater yield strengths than the nominal values.

Table 1 shows the pool of transversally stiffened hybrid steel plate girders subjected to patch loading found in the literature. A total amount of 72 girders tested by several authors can be included within this category. References and detailed information related to these tests can be found in [13].

The only experimental program intended to evaluate the response of a hybrid girder subjected to patch loading is the one presented by Schillings [18]. Reportedly, these tests were performed on fairly stocky web panels ($h_w/t_w = 36$). Furthermore, in this particular case, the $\Phi_h = f_{yf}/f_{yw}$ ratio was admittedly extreme ($f_{yf}/f_{yw} = 777/307 = 2.53$).

3. EN1993-1-5. Design of steel structures — Part 1–5: Plated structural elements

3.1. Hybrid girders

The European design rules EN1993-1-5 [20] overtly consider the hybrid girder usage. These rules take the premature yielding